Cosmic Microwave Weak lensing data as a test for the dark universe

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Combined analyses of WMAP 3-year and ACBAR Cosmic Microwave Anisotropies angular power spectra have presented evidence for gravitational lensing at > 3-σ level. This signal could provide a relevant test for cosmology. After evaluating and confirming the statistical significance of the detection in light of the new WMAP 5-year data, we constrain a new parameter A_L that scales the lensing potential such that $A_L = 0$ corresponds to unlensed while $A_L = 1$ is the expected lensed result. We find from WMAP5+ACBAR a 2.5-σ indication for a lensing contribution larger than expected, with $A_L = 3.1^{+1.8}_{-1.5}$ at 95% c.l.. The result is stable under the assumption of different templates for an additional Sunyaev-Zel'dovich foreground component or the inclusion of an extra background of cosmic strings. We find negligible correlation with other cosmological parameters as, for example, the energy density in massive neutrinos. While unknown systematics may be present, dark energy or modified gravity models could be responsible for the over-smoothness of the power spectrum. Near future data, most notably from the Planck satellite mission, will scrutinize this interesting possibility.

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I. INTRODUCTION

Results from the last decade of Cosmic Microwave Background (hereafter CMB) anisotropy observations have lead to a revolution in the field of cosmology (see e.g. [1], [2], [14], [3], [4], [5]). Many fundamental parameters of the cosmological model have now been measured with high accuracy. Moreover, since the standard cosmological model of structure formation, based on dark matter, inflation and a cosmological constant, is in reasonable agreement with the current observations, CMB anisotropies are now considered as a cosmological laboratory where fundamental theories can be tested at scales and energies not achievable on earth.

One crucial test concerns the nature of the dark energy component and the validity of General Relativity (GR, hereafter). The simple fact that supernovae type Ia observations are in agreement with an accelerating universe, which is puzzling in several theoretical respects, calls for the deepest possible investigation of dark energy and for a continuous test of GR.

CMB anisotropies are mainly formed at redshift $z \sim 1000$ when either dark energy or modifications to GR appear to be negligible. However, while CMB photons travel to us, they are affected and distorted by other, low redshift, mechanisms, that could help in understanding the nature of the accelerating universe.

The so-called late Integrated Sachs-Wolfe effect, for example, generated by the time-variation of the gravitational potential field along the CMB photon's line of sight in dark energy dominated universes, has already been detected by more than five groups by cross correlating galaxy surveys with anisotropies at very large angular scales (see e.g. [6]). While the statistical significance of the effect is still under 5σ, the detection represents a crucial test for dark energy [7].

On scales of ten arcminutes and smaller, the interaction of the CMB photons with the local universe starts to be dominant with second order anisotropies arising from weak lensing or scattering of the CMB photons off ionized gas in clusters and large scale structure (Sunyaev-Zel'dovich - SZ effect).

Weak lensing of CMB anisotropies could provide useful cosmological information. Gravitational lensing cannot change the gross distribution of primary CMB anisotropies, but it may redistribute power and smooth the acoustic oscillations in the CMB power spectrum (see e.g. [8]). Only in the tails of Silk damping ([9], at $\ell \gtrsim 3000$) the lensing contribution start to change the

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power spectrum significantly. Higher signal-to-noise can be achieved by correlating power in different directions on the sky, effectively using the four-point function signature imprinted by lensing to reconstruct the line-of-sight integrated matter distribution[1].

The strength of the weak lensing smoothing is related to the growth rate and amplitude of the dark matter fluctuations. Since both dark energy or modified gravity significantly affects these perturbations, a measurement of the CMB lensing, through its high-ℓ smoothing, can in principle be a useful cosmological test (see e.g. [10]).

The recent claim made by the ACBAR collaboration ([11]) for a detection of weak lensing, based solely on smoothing of the angular power spectrum, opens the opportunity for this kind of analysis. To first order, lensing causes the primordial peak structure to be less pronounced, as gravitational potential fluctuations on large scales mix the various scales in the primordial CMB power. Based on the effect on the power spectrum, the ACBAR collaboration has reported a $\Delta\chi^2 = 9.46$ between the lensed and unlensed best fits to the WMAP+ACBAR data, which translates into a $\geq 3\sigma$ detection of CMB lensing.

In this paper we further analyze this result and we study the possible cosmological implications. In the next section we phenomenologically uncouple weak lensing from primary anisotropies by introducing a new parameter A_L that scales the gravitational potential in a way such that $A_L = 1$ corresponds to the expected weak lensing scenario. We then constrain this parameter with current CMB data, we evaluate the consistency with $A_L = 1$, the correlation with other parameters and with other systematics such as SZ. We will report a $\sim 2\sigma$ preference for values of $A_L > 1$. We will then discuss some possible cosmological mechanisms that can increase the CMB smoothing, namely an extra background of cosmic strings and modified gravity.

II. ANALYSIS METHOD

Weak lensing of the CMB anisotropies enters as a convolution of the unlensed temperature spectrum C_ℓ with the lensing potential power spectrum C_ℓ^Ψ (see [8]). This convolution serves to smooth out the main peaks in the unlensed spectrum, which is the main qualitative effect on the power spectrum on scales larger than the ACBAR beam, or $6'$.

The weak lensing parameter is defined as a fudge scaling parameter affecting the lensing potential power spectrum:

$$C_\ell^\Psi \rightarrow A_L C_\ell^\Psi . \quad (1)$$

[1] This type of estimator has recently been used to find evidence of order $3-\sigma$ in the WMAP data [42, 43] in cross-correlation with galaxy surveys.

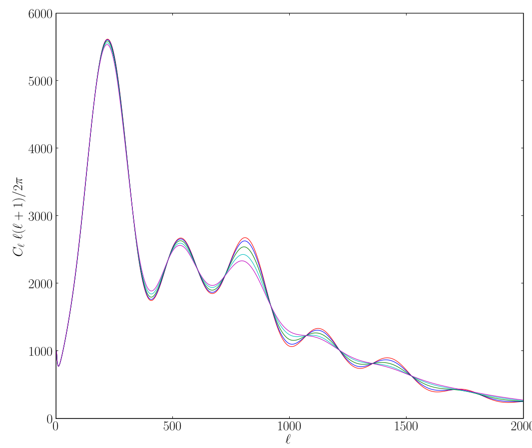

FIG. 1: This figure shows the effect of varying A_L parameter. The curves with increasingly smoothed peak structure correspond to values of A_L of 0,1,3,6,9.

In other words, parameter A_L effectively multiplies the matter power lensing the CMB by a known factor. $A_L = 0$ is therefore equivalent to a theory that ignores lensing of the CMB, while $A_L = 1$ gives the standard lensed theory. Since at the scales of interest the main effect of lensing is purely to smooth peaks in the data, A_L can also be seen as a fudge parameter controlling the amount of smoothing of the peaks. The Figure 1 illustrates this effect of varying A_L on a concordance cosmological model.

In what follows we provide constraints on A_L by analyzing a large set of recent cosmological data. The method we adopt is based on the publicly available Markov Chain Monte Carlo package `cosmomc` [17] with a convergence diagnostics done through the Gelman and Rubin statistics. We sample the following eight-dimensional set of cosmological parameters, adopting flat priors on them: the baryon and cold dark matter densities ω_b and ω_c, the ratio of the sound horizon to the angular diameter distance at decoupling, θ_s, the scalar spectral index n_S, the overall normalization of the spectrum A at $k = 0.002$ Mpc^{-1}, the optical depth to reionization, τ. Furthermore, we consider purely adiabatic initial conditions and we impose spatial flatness. We also consider the possibility of a massive neutrino component with fraction $f_\nu > 0$ and, finally, we add the weak lensing parameter A_L.

Our basis data set is the three–year WMAP data [3] (temperature and polarization) with the routine for computing the likelihood supplied by the WMAP team. As we were approaching completition of this paper, the five year WMAP result data became available ([4], [5]). We have therefore checked that our results are stable with respect to the new data.

We add the high quality and the fine-scale measurements from the ACBAR experiment ([11]) by using the

data set provided by the team, including normalization and beam uncertainties, window functions and the full error covariance matrix.

Finally, we also consider an "everything" data set. This adds other CMB experiments Boomerang 2K2 ([49]), CBI ([14]), VSAE ([15]), the large scale structure data in form of Red Luminous Galaxies power spectrum ([12]) and the supernovae measurements from SNLS ([16]), a prior on the Hubble's constant from the Hubble Key project ([13]) and, finally, a Big Bang Nucleosynthesis prior of $\omega_b = 0.022 \pm 0.002$ at 68% c.l. to help break degeneracies.

III. BASIC CLAIM AND ITS STATISTICAL SIGNIFICANCE

First we run two sets of Markov-chains with A_L fixed to 0 or 1. We measure the difference between the best fit lensed model and the best fit unlensed model of $\Delta\chi^2 = 9.34$, which is in excellent agreement with the original claim by the ACBAR team ($\Delta\chi^2 = 9.46$). Since both models have the same number of degrees of freedom, this has been interpreted in [11] as $> 3\sigma$ detection of the lensing signal.

Can this difference be attributed to a single point? As can be seen in the Table I, where we report the contribution to the overall χ^2 coming from the individual points (using the full covariance information) the answer is negative: the difference appears as randomly distributed across the 26 ACBAR points.

The effect is also marginally present in the WMAP third year and five year data. Considering only the WMAP third year result we found a $\Delta\chi^2 \sim 1.6$ between the $A_L = 1$ and $A_L = 0$ maximum likelihood model. Considering the newly released WMAP five year data ([3, 5]) which extend to higher ℓ we get $\Delta\chi^2 \sim 3.1$.

We can ask the question of significance in the Bayesian way, which should be more accurate in this relatively low signal-to-noise regime. In the Bayesian theory, the relative probability of a model (assuming the prior probabilities on each model are the same to start with) is given by its evidence, which is the integral of likelihood over the prior (see e.g. [18], [19]).

$$E = \int L(\theta) \mathrm{d}^N\theta \tag{2}$$

As shown in [20], the evidence can be written as

$$\log E = \log L_{\max} + \left(\frac{V_L}{V_\Pi}\right), \tag{3}$$

where $L_{\max}$ is the likelihood at the most likely point and V_L and V_Π are suitably defined volumes of posterior and prior.

The crucial point for this paper is that the evidence ratio for the lensed and unlensed model can be written simply as

$$\Delta \log E = \Delta \log L_{\max} + \Delta V_L, \tag{4}$$

since the prior volumes cancel exactly for the same underlying parameter space. The posterior volume can be roughly estimated as

$$V_L \propto \prod_i \sigma_i, \tag{5}$$

where σ_i are the marginalized estimates of the errors from the Markov Chains. A considerably better estimate would be to take the full error covariance into account, however, the models are so close that the noise in estimating the error covariance would probably dominate. This allows to estimate the evidence ratio to be

$$E_{\text{lensed}} - E_{\text{unlensed}} \sim 4.67 + 0.075 = 4.75 \tag{6}$$

ℓ_{eff}	$\Delta\chi^2$ (lensed)	$\Delta\chi^2$ (unlensed)
225	3.3	3.2
470	2.3	2.0
608	1.4	1.4
695	1.7	2.4
763	$9.5 \cdot 10^{-2}$	$1.3 \cdot 10^{-1}$
823	$3.3 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
884	2.2	2.3
943	1.0	1.8
1003	2.0	4.1
1062	$8.5 \cdot 10^{-2}$	$-1.7 \cdot 10^{-2}$
1122	$6.2 \cdot 10^{-2}$	$1.9 \cdot 10^{-1}$
1183	$6.5 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$
1243	$1.3 \cdot 10^{-1}$	$-3.6 \cdot 10^{-3}$
1301	$-3.9 \cdot 10^{-3}$	$3.1 \cdot 10^{-1}$
1361	1.7	2.3
1421	$1.2 \cdot 10^{-1}$	$3.4 \cdot 10^{-1}$
1482	4.1	4.9
1541	$1.3 \cdot 10^{-1}$	$4.5 \cdot 10^{-3}$
1618	1.4	3.6
1713	$1.4 \cdot 10^{-2}$	$-3.7 \cdot 10^{-2}$
1814	$3.0 \cdot 10^{-1}$	$3.2 \cdot 10^{-1}$
1898	$2.0 \cdot 10^{-1}$	$-3.5 \cdot 10^{-3}$
2020	$2.3 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$
2194	$2.7 \cdot 10^{-1}$	$5.5 \cdot 10^{-1}$
2391	2.3	2.5
2646	1.1	1.3
total	26.2	34.0

TABLE I: This is the contribution to the overall χ^2 coming from the individual points, using the full covariance information. This quantity is not constraint to be positive, as it is equal to $\Delta\chi^2_i = ((\vec{d}-\vec{t})^T C^{-1})_i (\vec{d}-\vec{t})_i$, where d denotes data vector, t denotes theory vector and C is the covariance matrix and there is no summation over repeated indices. This table shows that there are no significant outliers in the data as the overall contribution to χ^2 is evenly distributed across the bins. The signal is coming from a range of scales.

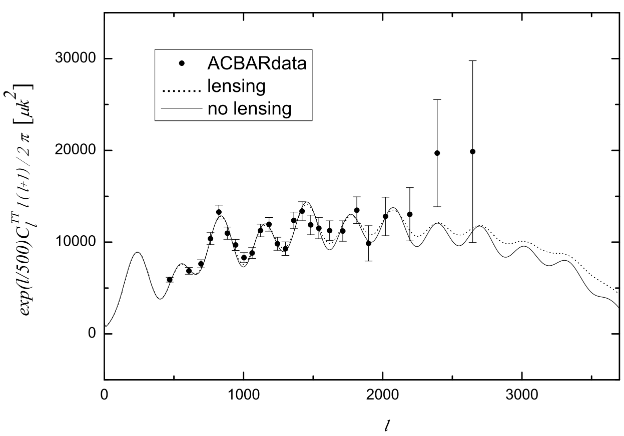

FIG. 2: This figure shows the ACBAR data with C_ℓ spectrum predictions suitably multiplied to show the structure of the peaks more clearly.

The net result is that the evidence difference is dominated by the best-fit effect: both theories are equally good at fitting the available parameter volume, however, the best-fit model is considerably better for the lensed model. In fact, the volume factor *strengthens* rather than weakens the evidence for lensing in the ACBAR data.

IV. VARYING A_L

However, the anticipated forecast for the ACBAR detection from Fisher matrix analysis is only at about 1-sigma level. How are the ACBAR results at a so much higher confidence limit?

The Figure 2 show the ACBAR points plotted against $C_\ell \ell(\ell+1)/2\pi \exp(\ell/500)$, where the exponent has been chosen to roughly counter-act the Silk's damping. We see that there is a weak "chi-by-eye" evidence that the ACBAR data are actually overly-smooth given the theoretical predictions and that this over-smoothness is driving up the detection.

We have therefore performed additional runs where we let A_L vary. We consider the case with WMAP3 data alone, with WMAP3+ACBAR data, and WMAP3+everything data sets. Our results are summarized in the top half of Table II and in Figure 3.

We see that the results prefer values of A_L which are considerably higher than unity. As we show below, the result is not affected by the inclusion of the Sunyaev-Zeldovich component. Therefore, the detection is coming from the smoothness of peaks, rather than excess of power on the smallest scales. This can also be seen "by eye" in the Figure 2.

The level of confidence for excess is above 2σ (except for the WMAP data alone case which is $\sim 1\sigma$) but less than three sigma away from one. In agreement with a

data set	model	limits on A_L
WMAP3	free A_l	$3.1^{+1.6+3.4}_{-1.7-2.8}$
WMAP3 + ACBAR	free A_L	$3.2^{+1.0+2.1}_{-0.9-1.7}$
WMAP3 + everything	free A_L	$3.3^{+1.0+1.9}_{-0.9-1.8}$
WMAP5	free A_l	$2.5^{+1.3+2.6}_{-1.2-2.1}$
WMAP5 + ACBAR	free A_L	$3.0^{+0.9+1.8}_{-0.9-1.6}$
WMAP5 + everything	free A_L	$3.1^{+0.9+1.8}_{-0.8-1.5}$
WMAP3 + ACBAR	+strings	$2.9^{+1.3+2.3}_{-1.2-1.8}$
WMAP3 + ACBAR	+SZ1	$3.1^{+1.0+2.2}_{-1.0-2.0}$
WMAP3 + ACBAR	+SZ2	$3.0^{+1.0+2.3}_{-1.0-1.8}$

TABLE II: . This table shows results for constraints on the A_L parameter. We report one and two sigma errors. Note that all results are statistically compatible with the standard prediction of $A_L = 1$ at the level of 2-3 σ.

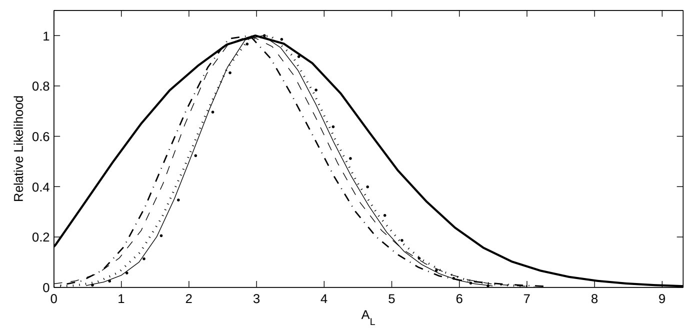

FIG. 3: Marginalized 1-D likelihood disribution for A_L for different datasets considered: WMAP3-alone (solid bold), WMAP3+ACBAR (dotted), WMAP3+"everything" (dotted bold), WMAP3+ACBAR+strings (solid), WMAP3+ACBAR+SZ1 (dashed), WMAP3+ACBAR+SZ2 (dotted-dash).

simple Fisher matrix forecast, we find a standard deviation of the lensing amplitude of $\Delta A_L = 1$. We also looked for correlations between A_L and other parameters and found them to be negligible for all other parameters.

Also in Table II we report a similar analysis but now cosidering the recent WMAP 5-year data release. As we can see, while the error bars are slightly reduced, the new data confirm the results obtained with the previous WMAP 3-year data.

How shall we interpret these results? Let us consider three possibilities:

1. *The result is a statistical fluctuation.* We note that the result is less than three sigma away from the theoretically most expected value of 1. The simplest explanation is that this is 2-3 σ statistical fluctuation, with data fundamentally in agreement with the lensed CMB theory. However, at the same time, the unlensed theory is deep in the tails of the A_L probability distribution and therefore has a considerably worse χ^2. In other words, ACBAR had a lucky noise realization to be able to claim detection of lensing.

2. *Hint of new physics.* It is possible that new physics is responsible for over-smoothness of the power spectrum. This is obviously the most interesting option. We explore these possibilities in further detail in the following two sections.

3. *Unknown foregrounds or experimental systematics.* A natural possibility is an unaccounted systematic in the experiment itself. CMB experiments are intrinsically difficult and despite many jack-knife tests that the authors have performed one should not exclude a possibility of a systematic that has slipped through. We discuss in the next section the possibility of an unknown foreground component.

V. ADDITIONAL COMPONENTS

We will now consider whether there could be an additional component that could bring about smoothing. It is possible that a smooth continuous component could lead to an effective smearing of the peaks when the adiabatic component where reduced by an appropriate amount. In order to check this idea we have tried to add three different templates, whose amplitude was allowed to be free-floating:

- *SZ template I.* A template expected from the Sunyaev-Zel'dovich effect as given by the analytic model of Komatsu and Seljak ([21]).

- *SZ template II.* A similar template based on smoothed particle hydro-dynamics simulations [47].

- *String template.* A template corresponding to "wiggly strings" of [22]. Note that the exact shape of the strings corresponding to a particular model is unimportant. The basic question we try to address is if a broad, featureless addition to the power spectrum can bring about a sufficient change.

Effect of these templates on the value of A_L is very small as shown in the results in the Table II and Figure 3. We conclude that while the data allow for some amount of extra smooth component, it by no means changed the "detection" of lensing.

VI. NON STANDARD MODELS

It is certainly important to investigate if there is any possibility to explain the anomaly through a mechanism based on non-standard physics. As we pointed out in the introduction both dark energy and modified gravity can change the growth and amplitude of dark matter perturbations and thus enhance in principle the CMB weak lensing signal.

Dark energy could affect the growth by changing the expansion history and by gravitational feedback of the perturbations in the dark energy component (see e.g [23], [24]). However quintessence scalar field models are generally unable to produce deviations larger than few percent of the CMB weak lensing signal. More exotic dark energy models with non-zero anisotropic stresses (see e.g. [25], [26]) could be responsible for the anomaly.

One should however consider the possibility that gravity is more complicated than anticipated by Einstein and that this modification causes more lensing. A feature common to a broad range of modified gravity theories is a decoupling of the perturbed Newtonian-gauge gravitational potentials ϕ and ψ. Whereas GR predicts $\psi = \phi$ in the presence of non-relativistic matter, a *gravitational slip*, defined as $\psi \neq \phi$, generically occurs in modified gravity theories (see e.g. [10, 27, 28, 29, 30, 31, 32, 33]).

Gravitational lensing phenomena depend directly on the sum of the two gravitational potentials and is strongly affected by a gravitational slip (see e.g. [34, 35, 36, 37, 38, 39, 40]). It is therefore interesting to investigate if $A_L > 1$ could be explained with modified gravity and to more quantitatively connect this parameter to modified gravity theories.

Since a very large number of models have been conceived here we use the parametrization of Daniel et al. 2008 ([41]), which is simple and easy to apply to several models. In this parameterization the gravitational slip is given by a function $\varpi(z)$ such that $\psi = (1 + \varpi)\phi$ and is parameterized by a single parameter ϖ_0 defined as

$$\varpi = \varpi_0 \frac{\Omega_\Lambda}{\Omega_m}(1 + z)^{-3}. \tag{7}$$

i.e. it starts to be relevant at dark energy (or modified gravity) appearance.

Following [41], we can easily approximate the relation between A_L and ϖ as

$$A_L(\varpi) = \left(\frac{G_\varpi(z = 2)}{G_{\Lambda CDM}(z = 2)}\right)^2 \left(\frac{2 + \varpi}{2}\right)^2 \tag{8}$$

The difference in growth factors is evaluated at $z = 2$, since the lensing kernel peaks at that redshift. Larger values of ϖ_0 correspond to larger values of A_L. A value of $\varpi_0 \sim 1.5$ could produces very similar results on the CMB to $A_L \geq 1.5$ and thus bringing the signal inside the $1 - \sigma$ cl. According to [41] this range of values of ϖ_0 is in agreement with the measured temperature anisotropy signal on very large angular scales but is at odds with the recent ISW detections.

VII. SYSTEMATICS

Let us in this section investigate what kind of systematic effect could mimic the observed over-smoothing in the data. As we have shown in Table I the effect is not coming for a particular rogue data point or a small range of scales. This further constrains possible sources.

First we note that most effects that produce smoothing in real space, such as inaccurate characterization of the beam or pointing will induce multiplication of the real power spectrum by the Fourier transform of the effective beam. This is unlikely to produce the additional smoothing required to explain the hint of an anomaly[2].

Atmospheric fluctuations could play a role. However in this case the effect would appear as an additional smooth background component and, as shown in Table II, our result appears stable under this assumption.

It may however be possible that an unaccounted for systematic is present in the data set provided by the ACBAR team, especially in the assessment of the sky window functions. Sky coverage of the ACBAR telescope is very complicated pattern of many fields with somewhat fuzzy edges. A poor characterization of the variation of noise across the fields could, in principle, lead to to the effect observed here. It however exceeds the scope of this paper to investigate this thoroughly.

Finally, it is possible that the error has been induced in the final power-spectrum estimation step of the data-reduction procedure. The maximum-likelihood estimator employed by the ACBAR team in principle assumes a step-wise power spectrum and the real shape of the power spectrum has to be accounted for carefully, especially at the signal-to-noise present in the ACBAR data.

It is clear that at the present stage systematic effects can not be ruled out and more data is needed. Fortunately, weak lensing will also produce a B-mode polarization signal that, if observed, will provide a fundamental cross-check.

VIII. CONCLUSIONS

We have reanalyzed the ACBAR angular power spectrum in light of the recent detection of a lensing signal in their angular power spectra. We tracked this down to a hint of over-smoothness in the power spectrum, detected at $\sim 2.5\sigma$ statistical significance. This over-smoothness pushed the theory without lensing deep into the tails and make it a poor fit to the data.

If interpreted as real, there are several interesting possibilities. A modified gravity can induce extra amount of lensing and we show that a gravitational slip could bring the discrepancy to sub 1-σ level.

How does this compare with other detection of lensing in the CMB. Two groups ([42],[43]) have searched for CMB lensing by correlating WMAP data. The WMAP data have lower intrinsic potential for measuring CMB lensing than ACBAR, however by using more information than the smearing of the C_ℓ structure (i.e. an optimal quadratic estimator), and by correlating to galaxy surveys, they were able to find significant evidence at the 3-σ level. While the mean value found is close to unity, these previous results allow considerable freedom in overall amplitude and a reasonable fit can be obtained with values of A_L lying somewhere in between. In particular $A_L \sim 1.7$ is compatible with both probes at less than 2 standard deviations. However a possible interpretation is that lensing is somehow enhanced inside the ACBAR field of view, which is only 1% of that of WMAP. It will be very interesting to apply quadratic estimator techniques using the full four-point function information to the ACBAR maps [48]. As the statistical error (based on Fisher matrix forecasting) for this probe is about 4 times smaller as compared to the smearing of acoustic peaks investigated here, we anticipate that this will shed light on the findings of the current paper.

Looking at closer measurements of lensing, the weak lensing tends to give values of σ_8 that seem only marginally higher than that of WMAP3 (see for example [44, 45, 46]) and consistent with the more recent WMAP5 measurements [5]. These measurements would limit the value $A_L \lesssim 1.2$. However, the redshift spans involved are considerably smaller with typical redshifts probed being around ~ 0.5. Therefore, the drastically different source redshifts imply that these results are not in direct contradiction and that it is conceivable that modified gravity models can be constructed that satisfy all observational constraints.

Maybe less excitingly, but more realistically, the feature should be interpreted as a noise realization fluctuation or explained by unaccounted systematics.

Future experiments as Planck, especially with the help of polarization data, will soon shed light on this intriguing result.

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